Soft Robot Motion Simulation in 2D Vascular-mimicking Network

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***Abstract*— Soft continuum robots with active steerable probes capable of navigating in a complex vascular network hold great promise for medical applications. This paper reports a simulation of a soft robot controlled by an external magnetic field to navigate in a 2D vascular network. We established a DER model for the soft robot and successfully controlled the equivalent force exerted by the magnetic field to follow the desired trajectory. The next step of this project includes integration of DER mode and PD controller, soft robot model refinement, and determining collision between the robot and walls.**

I. Introduction

Robot devices constructed with soft and flexible materials have desirable traits for medical applications, including limb rehabilitation, soft robot-assisted ultrasound imaging, medical procedures, etc. [1–3]. Minimally Invasive Surgery (MIS) utilizes small-scale surgical instruments inserted into the body through small incisions to access the target anatomies. Soft robotics devices hold great promise, particularly for MIS, such as eliminating thrombosis or lesions located at hard-to-reach anatomies due to their flexibility and low force execution [4]. Therefore, exponentially efforts have been made to implement soft robots in intracorporal procedures to reduce the incision area, recovery time and enhance patient safety. However, traditional soft robotics devices such as flexible endoscopes with rigid distal tip, which is commonly used, can only treat lesions located on the straight path and aimed against the endoscope [5]. The limited access area of the device hinders the application of this approach.

Constructing an actuated distal steerable mechanism is a potential solution to tackle the above challenge. Recent work on the simulation of a steerable probe demonstrated the capability to access more than 70% larynx area than along-the-axis laser in a non-steerable fiber probe [6], which indicates that the steerable probe can treat some the patients that cannot be treated otherwise. Despite the advantages of such a mechanism, several technical challenges blocked the clinical application. One major challenge is the large bending radius of the steerable probe due to the actuation mechanism, which results in a limited steering angle of the distal probe. Current research focuses on two types of actuation methods of the distal steering devices: 1) Tendon-driven continuum robot, where its steerable probe is driven by plastic wires embedded within the tube-like structures [7]. 2) Magnetically steerable continuum robot, where the steerable tip embedded with a tiny magnet deformed under external magnetic fields [8]. The cross-section radius of the latter mechanism can be much miniaturized due to its more straightforward structure, which results in greater flexibility compared with the tendon-drive one.

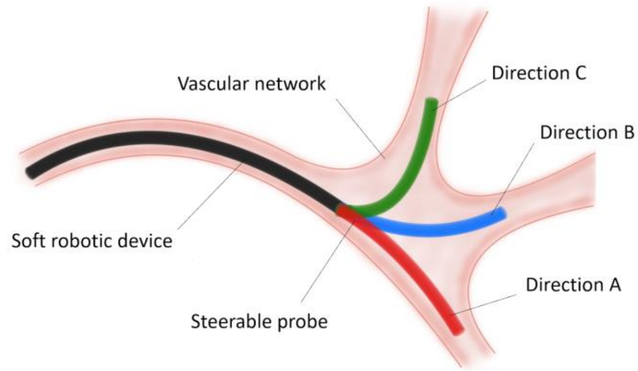

Figure 1. Illustration of an active steerable probe of a soft continuum robot navigating within a complex vascular network. Three configurations are listed to demonstrate different bending angles of the steerable distal tip.

Recent research on a soft robot utilizing a magnetically driven steerable probe has demonstrated its potential in the application of cardiac intervention, where its steerable probe was capable of navigating within a mimicked coronary artery [9]. However, due to the complexity of the real vascular structures with different radii of vessels, the real clinical implementation of this robot is still being investigated. Therefore, simulation of a soft robot navigating to the desired position within a constrained and complex environment is critical for the surgeons to determine the most suitable treatment for patients, as shown in Fig. 1. Additionally, the soft robot motion simulation paves the way for clinical application, especially in MIS.

This paper presents our midterm progress in the simulation of a soft robot device with a magnetically driven steerable tip capable of navigating through a complex 2D vascular-mimicking environment to the desired position. An elastic rod made of PDMS is adapted to simulate the soft robots, while a two-dimensional maze with a size of 1m*1m is adapted to simulate the vascular network. The magnetically driven steerable distal probe is simplified as an external force implemented on a specific node of the elastic rod. A PD controller adjusts the rod motion to follow desired trajectories. Currently, we demonstrate a simulation of controlling the node with an exerted force to run through the maze. Future work of this project includes integrating the Discrete Elastic Rod (DER) model with our current simulation; Defining the wall and adding physical interaction between DER and wall boundaries; Improving the quality virtual environment to mimic the vascular-mimicking network more vividly; potentially constructing and performing simulation in a 3D vascular virtual environment.

II. DESIGN AND METHOD

A. Vascular-mimicking Environment Model

To simulate the motion of a soft robot with a steerable probe navigating within a vascular network, we characterized both the soft robot and the vascular network with several conditions and assumptions. We only considered the robot's movement in a two-dimensional plane to simplify the construction of the virtual environment and reduce computational complexity. We created the 2D vascular mimicking environment in MATLAB with a size of 1m * 1m. To simulate the navigation capability of the steerable probe at an aneurysm, the intersection of several blood vessels, and the bending radius of the distal end, the 2D virtual network is designed to look like a maze with a random number of turns. The width of the channel is set to be 0.1m.

In the first stage of this virtual environment, all corners are designed to have a bending angle of 90 degrees. The starting point and ending point are located diagonally at the top-right and bottom-left corners of the maze. We also wrote a wall-follower algorithm to find the most direct path from the starting point to the endpoint, which is located at the centerline of every channel. This direct path is the ideal trajectory of the soft robot. The stiffness of the wall, as well as the friction and physical collision between the wall and the robot, are neglected for now.

B. Soft Continuum Robot Model

The soft continuum robot with a magnetically driven distal steerable probe is modeled as DER, a computation algorithm for rod-like object's physically based simulation. With this approach, we can simulate a robot's bending, stretching, and twisting in a torturous environment such as a blood vessel. The modeled rod is assumed to be made of Polydimethylsiloxane (PDMS), a commonly used material in the soft robotics field. The material properties of PDMS that would be used in the simulation are shown in Table 1 below [10,11]. The stiffness and friction coefficient of the PDMS would be induced in the next step to model the physical intersection with the virtual blood vessels. Fig. 2 shows the magnetically responsive distal tip of the soft robot resulting from the embedded tiny magnet under a vertical magnetic field. We characterized the magnetic effect as a force F exerted on a node at the distal tip while the rest of the node on the rod can be moved in free space.

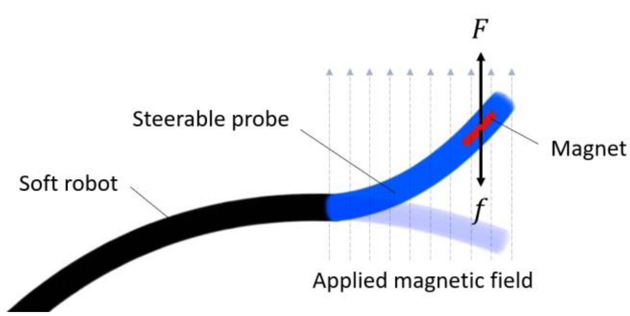

Figure 2. Schematic of the soft robot with the steerable probe under face-up vertical magnetic field. A magnet embedded in the frontal section of the distal tip produces force F that deflect the shape of the soft robot. Fluid resistance is represented by f, which is aligned to force F with the opposite direction.

TABLE I. PDMS MATERIAL PROPERTIES

Parameter	Value
Young's Modulus	1.47 MPa
Poisson's Ratio	0.48
Shear Modulus	0.497 MPa
Density	980kg/m^3

We induced fluid resistance to describe the friction when the soft robot passes through blood. The fluid resistance is assumed to be aligned with F in the opposite direction, which is defined as the equation shown below:

$$f = -\frac{1}{2}\rho v^2 A C_d$$

- ρ refers to the density of blood, which is approximately 1025 kg/m^3[12].
- v refers to the speed of a moving soft robot.
- A refers to the frontal area of the robot pushing through the blood. For our basic simulation, we consider this area to be equal to the cross-sectional area of the rod.
- C_d refers to the coefficient of drag, which is approximately 1.0536 [13].

From Newton's second law, the equation of motion for this system is described in the equation shown below:

$$f_i = m_i \frac{q_i(t_{k+1}) - q_i(t_k)}{dt^2} - m_i \frac{\dot{q}_i(t_k)}{dt} + \frac{\partial}{\partial q_i}\left(E_k^s + E_k^b\right) + F + f$$

- E_k^s refers to the stretching energy (Notes, equation 7.8).
- E_k^b refers to the bending energy (Notes, equation 7.10).
- f refers to the fluid resistance, which is derived in the above sections.
- F refers to the magnetic force, which is assumed to be exerted on a section of nodes near the distal end of the steerable probe.

As discussed in the class, Newton-Raphson iteration is implemented to solve the equation of motion at each time step. We also implemented the time marching method to compute the time evolution of the position of each node. The motion of the rod is controlled by changing the magnitude and direction of the force F in each time interval. In order to simplify the rod's movement, the force F is set to be equal to the fluid resistance so that the node with exerted force F would perform the uniform rectilinear motion.

C. Trajectory Following with Decentralized Feedforward PD Position Control

The trajectory of this soft continuum robot is indirectly controlled by the external magnetic field acting on the steerable probe part. By changing the direction and magnitude of the magnetic field, the movement of the robot's tip can be precisely controlled and follows a predefined trajectory. With the predefined 2-D maze and maze solution, the team generated a desired trajectory for the robot's tip to follow. To generalize the simulation, and mimic the real-world situation, a sin wave disturbance with 2-unit Amplitude and 10 rad/sec frequency is added to the robot model, which would cause some offset between the robot and desired trajectory.

$$Disturbance = 2 * \sin(10 * t)$$

The team decided to implement the Decentralized Feedforward Position and Velocity Control on a single node of the robot's tip and track the desired trajectory and compensate and disturbance. This method assumes that the rest of the robot body can be modeled as a Discrete Elastic Rod. Therefore, we can compute the soft continuum robot body movement with the DER method, which we learned in class, and combined with some external force from the blood viscosity and blood vessel.

The general principle of the Decentralized Feedforward Position and Velocity Control is computing the error values between the desired position, velocity, and real position and velocity. Then a Proportional and Derivative control (PD control) would be applied to compensate for these errors and add together with the desired trajectory. As a result, the real trajectory would slightly oscillate around the desired trajectory with proper proportional and derivative gain values.

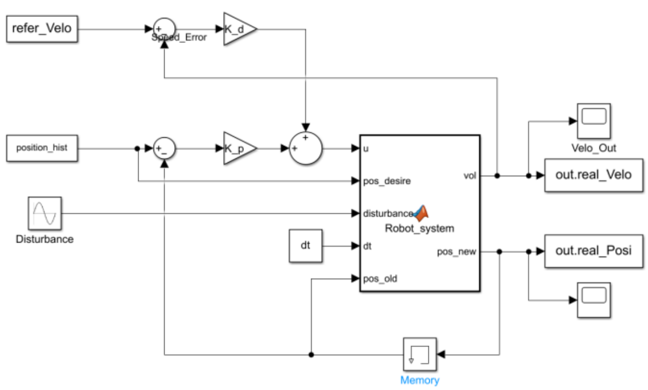

Figure 3. Decentralized Feedforward Position and Velocity Control Block Diagram with Sine Wave Disturbance.

III. Result

A. 2D Vascular-mimicking Maze

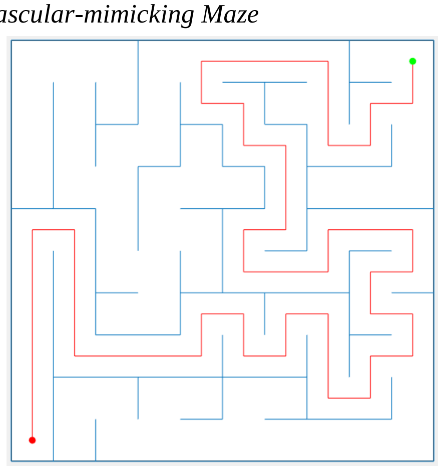

Figure 4. Illustration of the random-generated 2D vascular-mimicking maze. Red dot represents the starting point while green dot represents the end point. Blue lines represent the boundary wall; Red line represents the most direct path from the starting point to the end point.

B. Soft Robot Model

The initial configuration of the elastic rod is shown below in Fig. 5. The rod is constrained in x-y plane, and the first node is located at (0,0), which corresponds to the starting point of the vascular-mimicking maze.

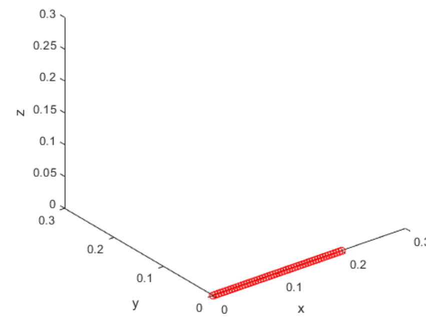

Figure 5. Illustration of the initial configuration of the elastic rod (red circular points) in MATLAB

C. Trajectory Following Simulation of a Single Node

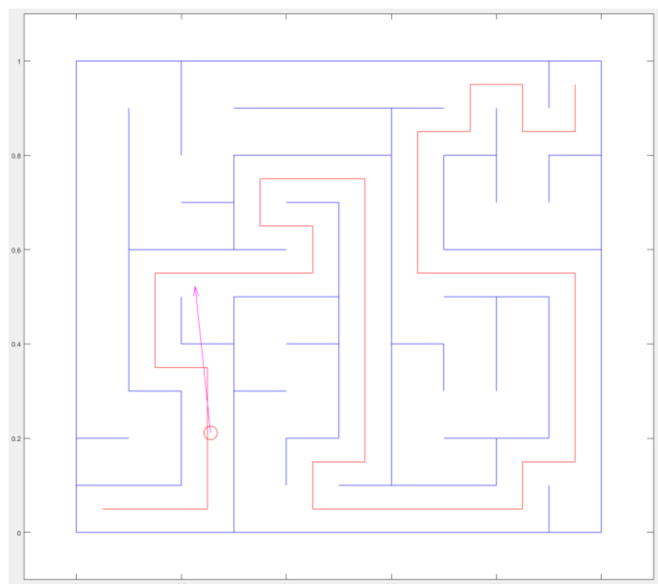

Figure 6. Soft Continuum Robot tip node trajectory following, with total magnetic force direction and magnitude applied to the node.

IV. Discussion & Ongoing work

A. DER and PD Controller Integration

We have accomplished the DER for the soft robot and a decentralized PD controller. To integrate these two parts, the exerted force F would be extracted from the PD controller in every time stamp, and then plugging into the equation of motion to perform simulation.

B. Soft Robot Model Refinement

The current soft robot model was simplified so that we could quickly verify the feasibility of our simulation method, which can be further refined mainly in two ways. We assumed that in each force direction, the contact area of the fluid resistance remains the same and equal to the cross-sectional area of the rod. In the real case, the fluid resistance would become larger while the angle between the looking-forward direction and the force direction becomes larger. Additionally, displacement restrictions between each node can be added to improve the accuracy of the simulation.

C. Collision between Rod and Boundary Walls

It is critical to consider the collision and friction between the soft robot and the inner wall of the blood vessels in clinical application. The position of each node at every timestamp would be stored and checked whether the robot has physical interaction with the wall. Node positions are also used to calculate the friction and normal force indirectly. The additional force produced during the rod movement would be added to the equation of motion in the next timestamp to determine the actual pose of the rod. Other parameters such as friction coefficient and the stiffness of both rod and walls would be included to calculate the resultant force.

D. Vascular-mimicking Environment Iteration

For the first iteration, the vascular-mimicking maze only includes walls in the horizontal and vertical directions. For the soft robot model, this maze could only test a scenario of a 90-degree bending angle. In the next iteration, a vascular network with sharp turns and multiple-channel-intersections will be developed to simulate the real vascular network. Constructing a sectional model of a real human vascular network is another option to further simulate the real environment, which helps pave a way for the implementation of the soft robot in clinical applications.

Link to the presentation video:
https://github.com/normanzmz/MAE259_Team8_Project/blob/main/Midterm_Progress/Presentation_Video.mp4

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